

Is the afterglow of Gamma Ray Burst 021004 unusual?

Shlomo Dado¹, Arnon Dar^{1,2} and A. De Rújula²

ABSTRACT

The bumpy light-curve of the bright optical afterglow (AG) of gamma ray burst (GRB) 021004, its spectral evolution and its radio emission have been claimed to be unusual. In the Cannonball Model of GRBs that is not the case. The very early AG's shape is, as for GRB 990123, a direct tracer of the expected circumburst density profile. The unprecedented precision of the data allows for the “resolution” of two cannonballs (CBs) in the AG. These two CBs correspond to the two pulses in the GRB and to the two wide humps in the AG light curve. The smaller wiggles in the AG are, as for GRBs 000301c and 970508, to be expected: they trace moderate deviations from a constant density interstellar medium. The observed evolution of the optical spectrum is that predicted in the CB model. The X-ray and radio emissions of GRB 021004 are also normal.

Subject headings: gamma rays: bursts—

Introduction

Instruments aboard HETE II detected GRB 021004 at 4.50432 UT October 2002 (Shirasaki et al. 2002). Its bright fading optical afterglow was discovered by Fox et al. (2002) within 10 minutes after the burst and was soon followed worldwide with many telescopes, quite continuously during the first few days. The unprecedented density and precision of the data are reported in Fig. 1. The redshift of the GRB's host galaxy, $z = 2.33$, was first correctly determined by Chornock and Filippenko (2002) and confirmed by Salamanca et al. (2002), Mirabal et al. (2002a), Savaglio et al. (2002), Castro-Tirado et al. (2002) and Matheson et al. (2002). The AG's brightness allowed precise measurements of its temporal decline, polarization, spectrum, and spectral evolution. The optical light-curves deviate from the smoothly steepening decline observed in most well studied optical AGs. There are also “unexpected” features in the spectrum (e.g., Salamanca et al. 2002; Mirabal et al. 2002b)

¹Physics Department and Space Research Institute, Technion, Haifa 32000, Israel

²Theory Division, CERN, CH-1211 Geneva 23, Switzerland

and its evolution (e.g., Matheson et al. 2002). The spectrum of the radio to submillimeter wavelengths was also claimed to be unusual (Berger et al. 2002).

In this letter we show that –in the CB model– the only unusual feature of GRB 021004 is the precision of the measurements. The most “surprising” of its properties were anticipated, in the sense that there are –again, in the CB model– precedents for them in past GRBs.

1. The Cannonball Model of GRBs

There is mounting evidence that long duration GRBs are produced in the explosions of supernovae akin to SN1998bw (Galama et al. 1998), by the ejection of ordinary baryonic matter –essentially ionized Hydrogen– in the form of plasmoids or “cannonballs” (CBs), with very highly relativistic Lorentz factors ($\gamma \sim 10^3$) (Dar and De Rújula 2000, 2001, Dado et al. 2002a,b,c,d) but otherwise similar to the ones observed in quasars (Marscher et al. 2002) and microquasars (e.g., Mirabel and Rodriguez 1994; Belloni et al. 1997; Mirabel and Rodriguez 1999; Rodriguez and Mirabel 1999 and references therein).

In the CB model (Dar and De Rújula 2000, 2001, reviewed in De Rújula 2002a,b) long duration GRBs and their AGs are produced in core collapse SNe by jets of highly relativistic CBs that pierce through the SN shell and the SN progenitor’s “wind” ejecta. A CB is emitted, as observed in μ -quasars, when part of an accretion disk falls abruptly onto the newly-born compact central object. Crossing the circumburst shells with a large Lorentz factor γ , the surface of a CB is collisionally heated to keV temperatures and the radiation it emits when it reaches the transparent outskirts of the shells —boosted and collimated by the CB’s motion— is a single γ -ray pulse in a GRB. The cadence of pulses reflects the chaotic accretion and is not predictable, but the individual-pulse temporal and spectral properties are. A long list of general properties (Dar and De Rújula 2001) of GRB pulses is reproduced in the CB-model, in which, unlike in the standard “fireball” models, the GRBs’ γ ’s have a thermal-bremsstrahlung —as opposed to synchrotron— origin³.

A CB exiting the circumburst shells soon becomes transparent to its own enclosed radiation. At that point it is still expanding and cooling adiabatically and by bremsstrahlung. The hard bremsstrahlung spectrum dominates the very early X-ray AG (for a few tens of seconds) with a fluence of predictable magnitude decreasing with time as t^{-5} . All X-ray AGs are compatible in magnitude and shape with this prediction (Dado et al. 2002a).

³In this (Ghirlanda et al. 2002), as in the relevance of the viewing angle, or the explanation of AG features by density inhomogeneities, the “standard” model is phagocytizing the CB-model’s views.

After the first tens of seconds, a CB’s emissivity is dominated by synchrotron emission from the electrons that penetrate in it from the interstellar medium (ISM). Integrated over frequency, this synchrotron emissivity is proportional to the energy deposition rate of the ISM electrons in the CB⁴. These electrons are Fermi accelerated in the CB’s tangled magnetic maze to a broken power-law energy distribution with a “bend” energy equal to their incident energy in the CBs’ rest frame. In that frame, the electrons’ synchrotron emission (prior to attenuation corrections) has an approximate spectral energy density (Dado et al. 2002b):

$$F_{\text{CB}}[\nu, t] = E_\gamma \frac{dn_\gamma}{dE_\gamma} \sim f_0 \frac{(p-2) \gamma^2}{(p-1) \nu_b} \frac{[\nu/\nu_b]^{-1/2}}{\sqrt{1 + [\nu/\nu_b]^{(p-1)}}}$$

$$\nu_b \simeq 1.9 \times 10^3 [\gamma(t)]^3 \left[\frac{n_p}{10^{-3} \text{cm}^{-3}} \right]^{1/2} \text{ Hz.} \quad (1)$$

where $p \approx 2.2$ is the spectral index of the Fermi accelerated electrons prior to the inclusion of radiation losses, f_0 is proportional to the ISM baryon density n_p , $\gamma(t) = 1/\sqrt{1 - \beta^2}$ (with $\beta = v/c$) is the Lorentz factor of the CBs, and ν_b is the “injection bend” frequency in the CB rest frame⁵. The radiation emitted by a CB is Doppler-shifted and forward-collimated by its highly relativistic motion, and redshifted by the cosmological expansion. A distant observer sees a spectral energy flux:

$$F_{\text{obs}}[\nu, t] \simeq \frac{(1+z) \delta(t)^3 R^2 A(\nu, z)}{D_L^2} F_{\text{CB}} \left[\frac{(1+z) \nu}{\delta(t)}, \frac{\delta(t) t}{1+z} \right], \quad (2)$$

where R is the radius of the CB (which in the CB model tends to a calculable constant value $R_{\text{max}} = \mathcal{O}(10^{14})$ cm, in minutes of observer’s time), $A(\nu, z)$ is the total extinction along the line of sight to the GRB, $D_L(z)$ is the luminosity distance⁶ and $\delta(t)$ is the Doppler factor of the light emitted by the CB:

$$\delta(t) = \frac{1}{\gamma(t) (1 - \beta(t) \cos \theta)} \simeq \frac{2 \gamma(t)}{1 + \theta^2 \gamma(t)^2}, \quad (3)$$

where θ is the angle between the CB’s direction of motion and the line of sight to the observer. The last approximation is valid in the domain of interest for GRBs: $\gamma^2 \gg 1$ and $\theta^2 \ll 1$. The total AG is the sum over CBs (or large individual GRB pulses) of the flux of Eq. (2).

⁴The kinetic energy of a CB is mainly lost to the ISM protons it scatters; only a fraction $\leq m_e/m_p$ is re-emitted by electrons, as the AG.

⁵This bend frequency is not the conventional “cooling break”. It reflects an *injection bend* in the electron spectrum at the energy $E_b = \gamma(t) m_e c^2$ with which the ISM electrons enter the CB at a particular time in its decelerated motion (Dado et al. 2002b).

⁶The cosmological parameters we use are: $H_0 = 65 \text{ km}/(\text{s Mpc})$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

For an ISM of constant baryon density n_p , the deceleration of the CBs results in a Lorentz factor, $\gamma(t)$, that is given by (Dado et al. 2002a):

$$\begin{aligned}\gamma &= \gamma(\gamma_0, \theta, x_\infty; t) = \frac{1}{B} \left[\theta^2 + C \theta^4 + \frac{1}{C} \right], \\ C &\equiv \left[\frac{2}{B^2 + 2\theta^6 + B\sqrt{B^2 + 4\theta^6}} \right]^{1/3}, \\ B &\equiv \frac{1}{\gamma_0^3} + \frac{3\theta^2}{\gamma_0} + \frac{6ct}{(1+z)x_\infty},\end{aligned}\tag{4}$$

where $\gamma_0 = \gamma(0)$, and $x_\infty = N_{\text{CB}}/(\pi R_{\text{max}}^2 n_p)$ characterizes the CB’s slow-down in terms of N_{CB} , its baryon number and R_{max} , its radius (it takes a distance x_∞/γ_0 , typically of $\mathcal{O}(1)$ kpc, for the CB to slow down to half its original Lorentz factor).

The extinction, $A(\nu, t)$ in Eq. (2), can be estimated from the difference between the observed spectral index *at very early time when the CBs are near the SN* and that expected in the absence of extinction ($F_{\text{obs}} \propto \nu^{-0.5}$, for $\nu \ll \nu_b$). The CB model predicts—and the data confirm—the gradual evolution of the effective optical spectral index towards the constant value ≈ -1.1 observed in all “late” AGs (Dado et al. 2002a). The “late” index is independent of the attenuation in the host galaxy, since at $t > 1$ (observer’s) days after the explosion, the CBs are typically moving in the optically-transparent halo of the host galaxy.

The comparison of the predictions of Eq. (2) with the observations of optical, X-ray and radio light-curves and spectra is discussed in Dado et al. (2002a,b). The results—for *all* GRBs of known redshift—are very simple, satisfactory and parameter-thrifty. The CB-model results concerning X-ray lines in GRB AGs are also exceptionally predictive, simple and encouraging (Dado et al. 2002e).

2. GRB 021004 in the CB model

Five properties of AGs in the CB model are particularly relevant to GRB 021004:

- a. For most GRB optical AGs good fits are obtained by approximating the ISM-density by a constant (Dado et al. 2000a,b,c,d). One exception is the optical AG of GRBs “caught” at very early times, when the CBs are still moving in a wind-generated $1/r^2$ density profile. In the CB model the AGs’ flux is proportional to the swept-up electron density, implying $F_{\text{obs}} \propto 1/t^2$ at very early times, as observed in GRB 990123 and GRB 991216.
- b. The achromatic “bumps” in the AGs of GRB 970508 and GRB 000301c are explained (Dado et al. 2002a,b) by inhomogeneities in the density along the CBs’ trajectory, better

than by gravitational lensing (Garnavich, et al. 2000). Density changes are expected within star formation regions and upon exit from the superbubbles where most of the SNe take place (Dado et al. 2000a).

c. The data on past AGs were coarse enough or started late enough for the contributions of different CBs (which can often be resolved as individual pulses in the GRB phase) to coalesce into an AG contribution describable as a single CB or a collection of similar ones. But individual CBs have different properties, and may even be emitted at somewhat different angles, due to precession of the accretion disk relative to the rotation axis of the compact object (Fargion and Salis 1995), as observed in the microquasar SS 433 (Margon 1984).

d. The spectral shape of the AGs and their time-evolution, in particular their steepening at the time-varying frequency ν_b of Eq.(1) towards $\nu^{-1.1}$ at late time is very well supported by the data (Dado et al. 2002b).

e. The excess polarization of AGs above that induced by the ISM in our Galaxy may be largely due to the host galaxy’s ISM. In that case, it should be correlated with the extinction in the host and decline with time as the CBs move into the halo.

The γ -ray light curve of GRB 021004 shows two prominent pulses separated by ~ 30 seconds (Shirasaki et al. 2002 and <http://space.mit.edu/HETE/Bursts/GRB021004/>). In the CB model, these correspond to two dominant CBs. The good quality of the optical data for GRB 021004 —and its double-humped γ burst— make irresistible the temptation to fit its broad band AG light curves with **two CBs**, emitted in the same direction θ relative to the observer⁷, but with otherwise free parameters (normalization, γ_0 and x_∞). We fix the spectral index p in Eq. (1) to the expected $p = 2.2$, assume a density profile of the form $n(r) = n_\infty [(r_0/r)^2 + 1]$, and fit simultaneously all the reported NIR, optical and radio data.

NIR-Optical AG: In Fig. 1 we compare the results of the CB-model’s fit to the data for the NIR-optical lightcurves. We have corrected for selective Galactic extinction in the direction of GRB 021004, $E(B - V) = 0.06$ (Schlegel et al. 1998), (attenuation magnitudes $A_U = 0.33$, $A_B = 0.26$, $A_V = 0.20$, $A_R = 0.16$, $A_I = 0.12$, $A_J = 0.08$, $A_K = 0.04$, and $A_H = 0.01$, in the various bands). Extinction in the host galaxy and intergalactic absorption at wavelengths blueward of the $\text{Ly}\alpha$ limit at 4054 \AA were not included, nor a possible contribution from the host galaxy to the late AG. The results are very satisfactory though, as befits a rough approximation to a no-doubt very complex system, it is not perfect ($\chi^2 = 6.7$ per d.o.f. for 172 not cross-calibrated data points, if the uncertainties are indeed as small as reported, or

⁷We have also made fits with two different values of the emission angles θ . They do not improve χ^2 significantly, and yield similar parameters: two different emission angles are not really necessary.

$\chi^2 = 1.7$ per d.o.f. if all reported uncertainties < 0.05 magnitude are replaced by 0.05 mag). The broad-band fitted parameters are, $\theta = 1.73$ mrad, $\gamma_0[1] = 1011$, $\gamma_0[2] = 910$ (implying $\delta_0[1] = 500$, $\delta_0[2] = 524$), $x_\infty[1] = 14$ kpc and $x_\infty[2] = 430$ kpc. To demonstrate the real quality of the fit, we have blown up the R-band results in Fig. 2. In the region between ~ 0.5 and ~ 5 days, the data “wobble” by as much as 20% around the theoretical curve. It would be easy to correct for this by assuming similar deviations of the ISM density relative to the adopted constant value, clearly a moot exercise.

Optical Polarization: The observed polarization of the optical AG of GRB 021004, consistent with that induced by the ISM in our Galaxy (Covino et al. 2002; Rol et al. 2002; Wang et al. 2002) is also consistent with the negligible attenuation, and consequently small polarization induced by the host’s ISM, as expected in the CB model.

X-ray AG: The Chandra observations by Sako et al. (2002) in the 2-10 keV domain, from 0.867 to 1.874 days after burst, result in a spectrum $dn/dE \propto E^{-2.1 \pm 0.1}$ and an AG decline $dn/dt \propto t^{-1.0 \pm 0.2}$, both consistent with the optical observations and with the CB-model’s expectations: $dn/dE \propto E^{-2.1}$ and, except at earlier times, an achromatic light-curve. In this GRB, as in most others, the temporal and spectral behaviours are similar in the optical and X-ray bands, as shown in Fig. 1, but synchrotron emission alone underestimates the X-ray fluence (in this case, the optical to X-ray effective index is 0.2 units less steep than the separate indices). The CB-model explanation is that in the X-ray domain not only synchrotron radiation, but also Compton up-scattering and line-emission contribute to the flux (Dado et al. 2002a,b). There is nothing exceptional in the X-ray data for GRB 021004.

Radio and Submillimeter AG: In Fig. 3 we compare the results of the CB-model’s broad-band fit to the radio and submillimeter data. Unlike the X-ray and optical AGs, the radio AGs are sensitive to self-absorption in the CBs, parametrized by a single absorption frequency ν_a (Dado et al. 2002b). The fit values are $\nu_a[1] = 0.65$ GHz and $\nu_a[2] = 0.37$, similar to those of other GRBs with close-by parameters, in particular 000301c, for which $\gamma_0 = 1061$ and $\theta = 2.32$ mrad and $\nu_a[2] = 0.55$ GHz (Dado et al. 2002b). The fit in Fig. 3 is very satisfactory, in particular in view of expected scintillations in the radio data. The CB model is seen to correctly predict the early temporal increase (to be followed by a later turn-over due to self absorption) and the spectral behaviour ($F_\nu \sim \nu^{1.13 \pm 0.15}$ between 1.43 GHz and 86 GHz before the turn-over), also similar to those observed in GRB 000301c (Rol et al. 2000; Berger et al. 2000). GRBs 021004 and 000301c also have very similar redshifts and fluences, dim host galaxies, bumpy light-curves and “late” optical AGs (GRB 000301c was optically detected after ~ 2 days by Fynbo et al. 2000).

The GRB proper. In the CB model (Dar and De Rújula 2000), the rest-frame fluence of a CB viewed at a small θ is amplified by a huge factor, δ_0^3 , due to the Doppler boost

and relativistic beaming of the radiation (Shaviv and Dar 1995). In Dado et al. (2002a) we deduced that the GRB photons of the GRBs of known redshift correspond to a total energy release in the CBs’ rest system that is in a surprisingly narrow interval⁸, $10^{44 \pm 0.3}$ erg, and that the spread in the “equivalent spherical energies” E_γ around their mean, $\bar{E}_\gamma \approx 4 \times 10^{53}$ erg, is mainly due to the spread of their Doppler factors (deduced from the fits to their AGs) around their mean: $\bar{\delta}_0 \approx 10^3$. For GRB021004, $\delta_0 \approx 500$. The CB model expectation is $E_\gamma \approx \bar{E}_\gamma (\delta_0 / \bar{\delta}_0)^3 \approx 5 \times 10^{52}$ erg, in agreement with the observed $\approx 4.8 \times 10^{52}$ erg (we have corrected the value of Lamb et al. (2002) to a redshift $z = 2.335$, from their adopted $z = 1.6$). The GRB of GRB 021004 is also entirely normal and its equivalent spherical energy is also close to that of GRB 000301c: $E_\gamma \approx 4.6 \times 10^{52}$ erg.

Spectral Variability: The energy dependence of the injection bend implies that the optical spectra, $F_{\text{obs}}[\nu, t]$, typically steepen in the first few days, as the bend frequency in the observer’s frame $\nu_b^{\text{obs}}(t) = \nu_b(t) \delta(t) / (1 + z)$ “crosses” the optical band (Dado et al. 2002b). Let $\lambda_b^{\text{obs}}(t) = c / \nu_b^{\text{obs}}(t)$. Given the parameters of our fit to the optical AG, we can predict, by use of Eqs.(1), the spectral energy density F_λ as a function of the ISM density n_p . The two CBs of GRB 021004 have similar γ_0 and δ_0 but different x_∞ : their time evolution and injection bends are different. The AG is dominated before and after $t \sim 0.4$ days by one or the other CB, whose properties determine the “early” or “late” spectral evolution. The results for the spectral ratio at the “late” times ($t_1 = 0.756$ d, $t_2 = 2.786$ d) reported by Matheson et al. (2002) are shown in Fig. 4. The upper panel in this figure is the prediction for $n_p = 0.01 \text{ cm}^{-3}$, for which $\lambda_b^{\text{obs}}(t_1) = 3320 \text{ \AA}$ and $\lambda_b^{\text{obs}}(t_2) = 7790 \text{ \AA}$.

The interpolation between the limiting behaviours at $\nu \ll \nu_b$ and $\nu \gg \nu_b$ could be more abrupt than in Eq. (1). In the lower panel of Fig. 4 we show the result for a sharp transition, for which, with $n_p = 0.02 \text{ cm}^{-3}$, $\lambda_b^{\text{obs}}(t_1) = 2350 \text{ \AA}$ (below the measured range) and $\lambda_b^{\text{obs}}(t_2) = 5500 \text{ \AA}$, at which point F_λ changes from $\sim [\lambda / \lambda_b]^{-1.5}$ to $\sim [\lambda / \lambda_b]^{-0.9}$, so that the ratio shown in the figure is $[\lambda / \lambda_b(t_2)]^{-0.6}$ below 5500 \AA , and unity above.

3. Conclusions

We have shown that the CB-model’s interpretation of all the data concerning GRB 021004 is quite simple and very successful. The only novelty is that, relative to other GRB AGs, the R-band optical data start very early and are so copious that a single CB would not fare well in explaining the R-band light-curve’s shape. Two large pulses are observed in the GRB light curve, enticing one to fit the rest of the data with two CB contributions. The

⁸GRBs in the CB model are much better standard candles than in the standard model (Frail et al. 2001).

results are excellent and do not require new ad-hoc assumptions about the circumburst ISM density: GRB 021004 fits well and naturally along all other GRBs of known redshift.

Having described a relatively simple AG evolution with so many parameters (7 to 9, if the “radio” parameters ν_a are counted) we cannot claim that they are uncorrelated and truly well determined. We regard this exercise as an existence proof of a CB-model understanding of the bumpy AG of GRB 021004.

It is, as usual, instructive to compare the CB-model’s results to those of the standard “fireball” scenarios. One of the most striking differences is often the degree of simplicity; the explanation of the alleged X-ray lines in GRB afterglows is an extreme case⁹. The GRB under discussion is also in an extreme class: its standard explanations (Lazzati et al. 2002, Nakar et al. 2002) require the model-dependent inversions of the observed R-band light curve to obtain the input function (the ISM density profile) needed to “predict” the output function (the R-band light curve). It would be difficult, on these grounds, to falsify a model with that much freedom.

For a non-constant ISM density, short-time spectral variations and AG features are expected in the CB model due to the local instantaneous dependence of ν_b on the density, Eq. (1). These are not expected in the standard models because signals emitted at a fixed t from different portions of the fireball or firecone are observed at different times and with different Doppler boosts, erasing all effects of width $\Delta t \ll t$. Moreover, the standard AG fluence depends on the integrated density (up to time t): an abrupt rise of fluence such as that observed in GRB 970508 requires a different explanation (the AG is “re-energized”, as in Piro et al. 1998). A similarly abrupt dip would be unexplainable.

The CB model is very modest in the adjectives that refer to GRBs. None of them is exceptional, not even the very energetic GRB 990123, nor 970598 with its peculiar AG shape, nor the extraordinarily close-by 980425. They are all associated with supernovae, seen when they are visible, not seen when they are not (Dado et al. 2002a). The explosions that generate GRBs are not “the biggest after the Big Bang”. The mechanism that begets GRBs is common: it takes place in quasars and microquasars as well. The model works very well and is very predictive, thus falsifiable.

Acknowledgment: This research was supported in part by the Helen Asher Space Research Fund and by the VPR fund for research at the Technion. Useful remarks by Stephen Holland are gratefully acknowledged.

⁹In the CB model the existence and energies of the lines are predicted, requiring no custom-made Fe envelopes nor any other ad-hoc assumption (Dado et al. 2002e).

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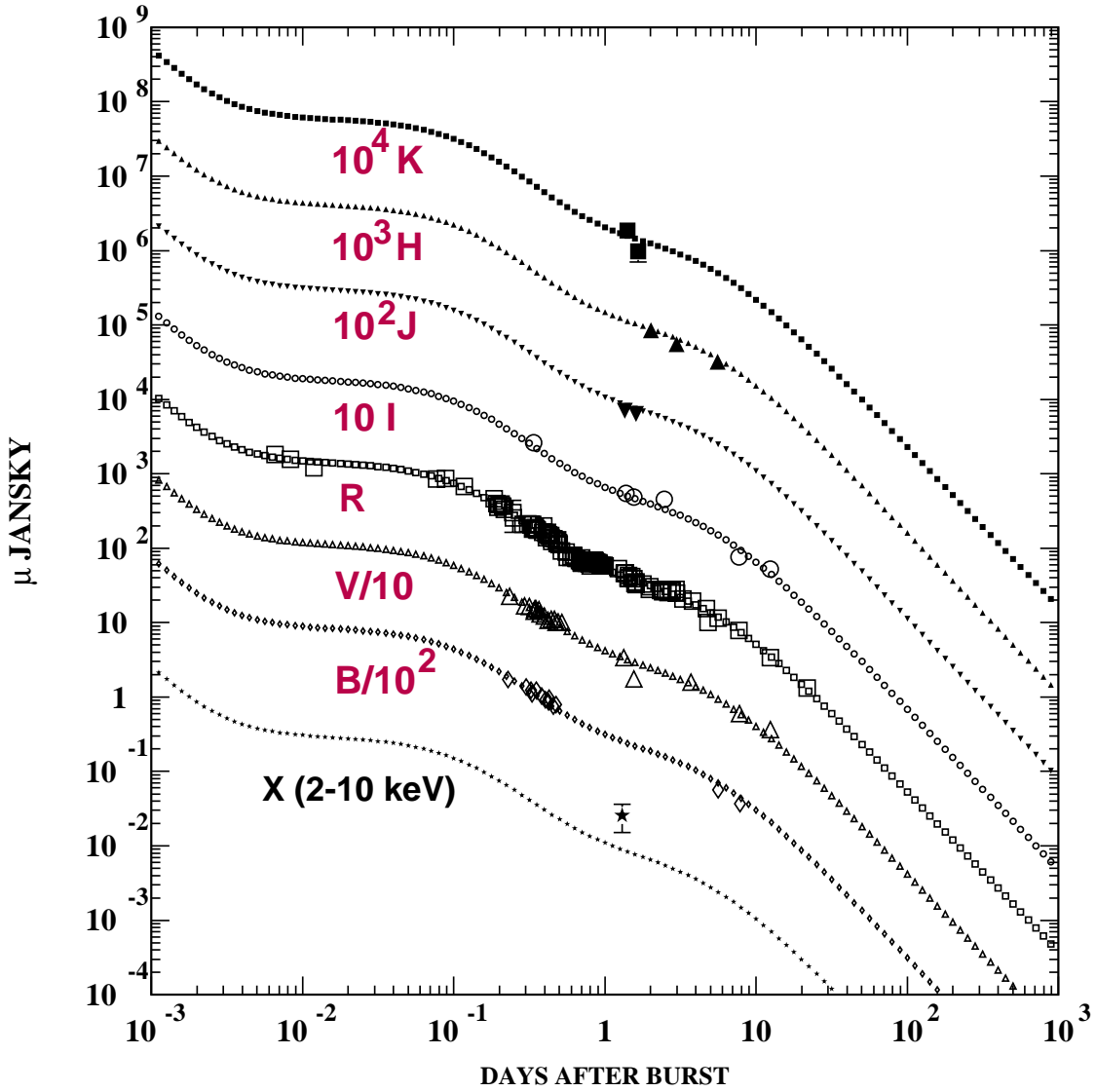


Fig. 1.— Comparison between the NIR–optical observations of the AG of GRB 021004 and the CB model fit for two CBs with different parameters, each contributing as in Eqs. (1) to (4). The ISM density was assumed to be a constant plus an additional “wind” contribution decreasing as $1/r^2$. The figure shows (from top to bottom) 10^4 times the K band, 10^3 times the H band, 10^2 times the J band, 10 times the I-band, the R-band, 10^{-1} of the V-band and 10^{-2} of the B-band. These data are from: Fox et al. 2002; Matsumoto et al. 2002a,b; Oksanen et al. 2002a,b; Weidinger et al. 2002; Winn et al. 2002; Zharikov et al. 2002; Halpern et al. 2002a,b; Balman et al. 2002; Anupama et al. 2002; Cool et al. 2002; Holland et al. 2002a,b; Bersier et al. 2002; Sahu et al. 2002a,b; Torii et al. 2002; Covino et al. 2002a,b; Stanek et al. 2002; Rhoads et al. 2002; Mirabal et al. 2002a,b; Masetti et al. 2002; Barsukova et al. 2002; Malesani et al. 2002a,b; Klotz et al. 2002a,b; Di Paola et al. 2002; Stefanon et al. 2002; Lindsay et al. 2002a,b; and Williams et al. 2002; all recalibrated with the observations of Henden et al. (2002). The bottom line is the CB model prediction of the synchrotron contribution to the 2–10 keV X-ray AG (Datum is from Sako et al. 2002).

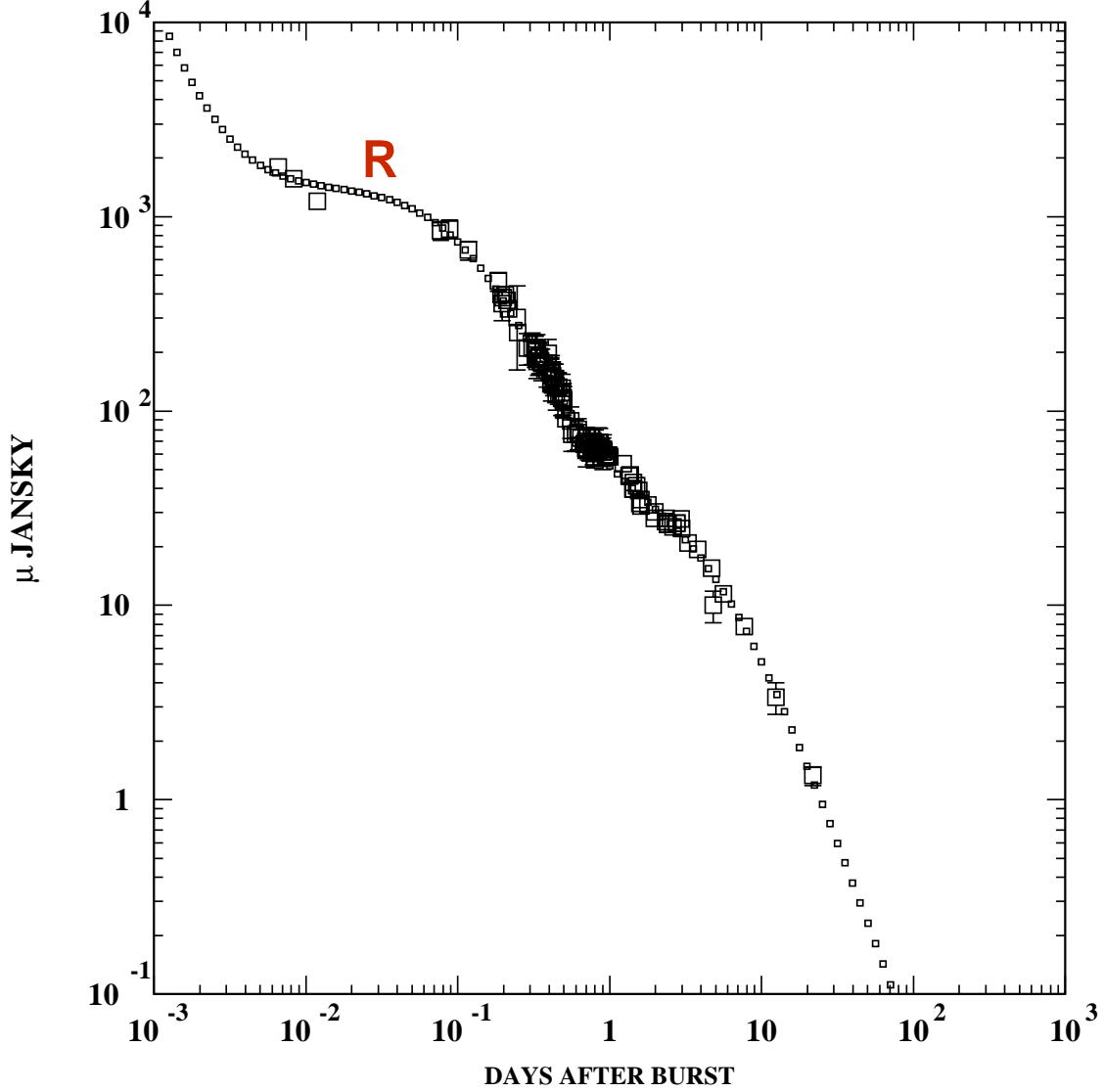


Fig. 2.— The R-band results shown in Fig. 1 blown up. The ISM density was assumed to be a constant plus an additional “wind” contribution decreasing as $1/r^2$. The wind contribution is only significant at $t < 0.01$ days, after which the CBs are more than 1 pc away from the progenitor. The “wind” is also seen in other AGs observed early enough (Dado et al. 2002a).

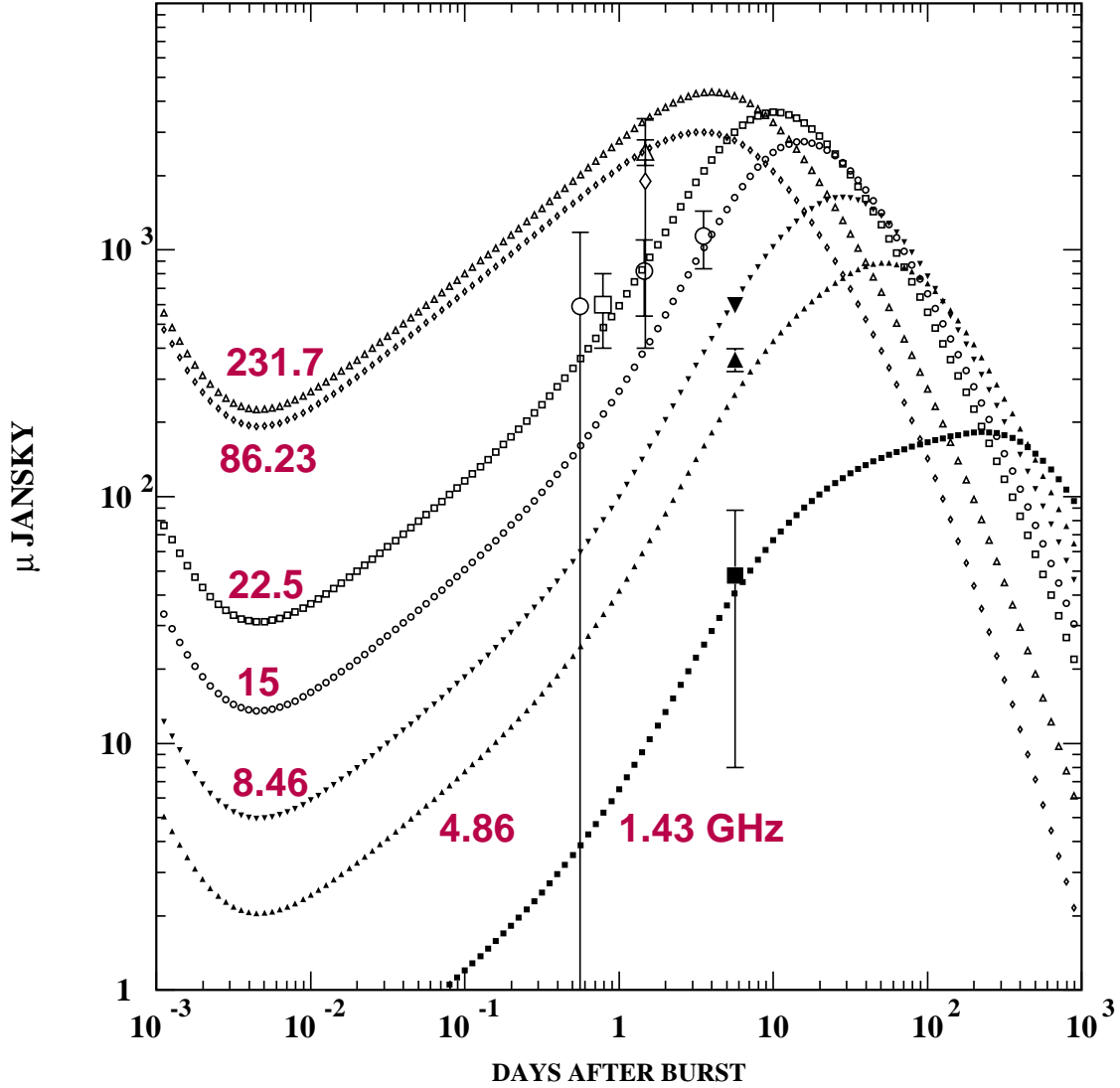


Fig. 3.— Comparison between the radio and submillimeter observations of the AG of GRB 021004 and the CB model light curves calculated from the broad band fit to its AG with two CBs with different parameters, each contributing as in Dado et al (2002b). The figure shows (from bottom to top) the data and the predicted lightcurves at 1.43, 4.86, 8.46, 15, 22.5, 86.23 and 231.7, GHz. Data points are from Frail et al. 2002, Berger et al. 2002a,b; Pooley et al. 2002a,b,c and Bremer et al 2002. The symbols for the data are the same as those for the theoretical curves.

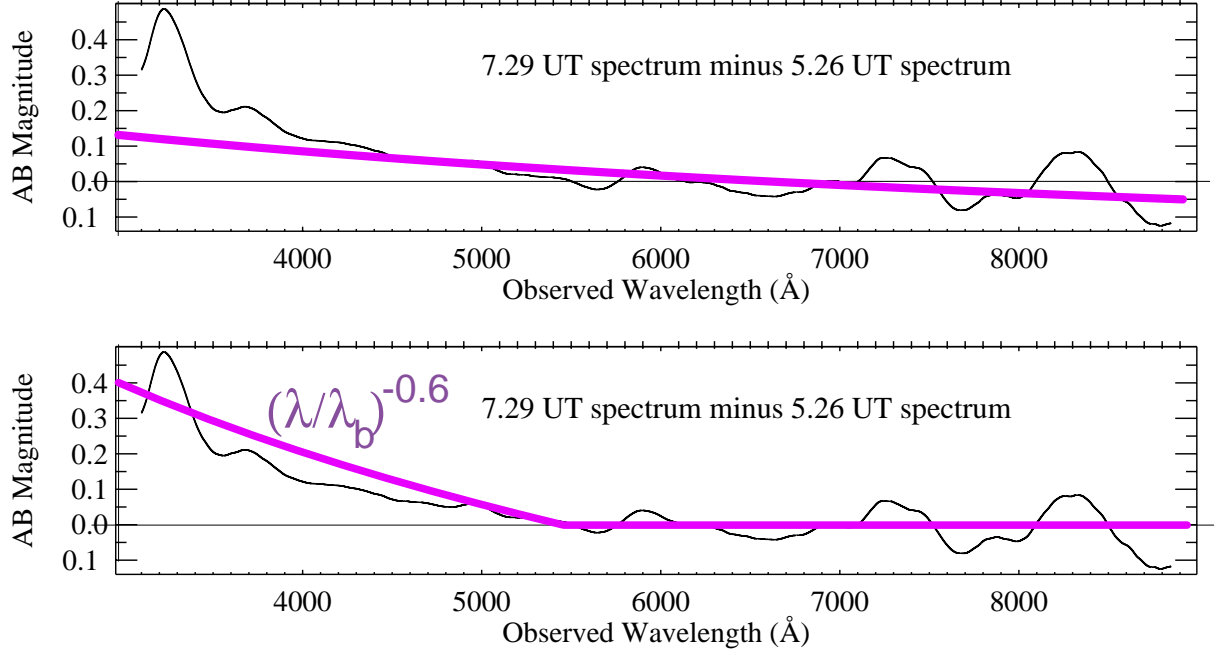


Fig. 4.— Comparison between the ratio of the spectra (F_λ) of the optical afterglow of GRB 021004 at $t_1 = 0.756$ days and $t_2 = 2.786$ days after burst, normalized to ~ 1 at long wavelengths, as measured by Matheson et al. (2002). The wiggles on the curve extracted from observations are artifacts of the smoothing procedure, the error in the plotted magnitude difference is estimated at 0.1 mag. The thick line in the upper panel is the prediction from Eq. (1), the one in the lower panel illustrates an abrupt injection bend at $\lambda = \lambda_b(t_2)$.